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Sedimentological and provenance analysis of the Cretaceous Moro Formation Rakhi Gorge, Eastern Sulaiman Range, Pakistan

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Abstract

The Cretaceous Moro Formation from the Rakhi Nala section Dera Ghazi Khan has been studied in detail to investigate the Sedimentology and provenance. This paper describes the litho-facies changes, depositional environment, and provenance analysis of the Cretaceous Moro Formation from the Rakhi Nala section, eastern Sulaiman Range. The studied Formation is 110-140 meters thick and consists mainly of fine to coarse-grained sandstone, with minor-siltstone, mudstone (claystone, shale), and limestone. The uppermost beds of the Moro Formation are consist of sandstone with iron types of cement. Twelve lithofacies have been identified based on a petrographic investigation related to the depositional environment of the Moro Formation ranging from deltaic to marine setting (Delta Plain-Delta front). Petrographic analysis of sandstone reveals the presence of quartz both, mono-crystalline and poly-crystalline, less feldspar; heavy minerals like hematite and magnetite, and glauconite were found in negligible amounts. Detrital mineral composition shows that in Moro Formation, the sandstone shows a litharenite. Modal composition of the sandstone from the QFL diagram was Q 66% F 0.3% L 33.7% and that of the QmFLt diagram was QM, 57% F 0.23% L 43.77%. The overall average composition is Q 61.5% F 0.27% L 38.7%. A total of 37 thin-sections are studied for provenance analysis, out of which twenty-seven samples are considered as Litharenite (this shows recycled, or craton interior origin), eight Quartz arenite categories are identified and two samples are fall in the sublitharenites category (Quarts recycled source area).

Keywords: *Lithofacies, Late Cretaceous, Moro Formation, Provenance, Eastern Sulaiman Range.*

1. Introduction

Ancient sedimentary environments can be reconstructed through assessing sedimentary facies, facies associations, sedimentary structures, and assessment of trace fossil assemblages types. The depositional environment can be identified from lithofacies. Characterization and description of Formations require investigation of the physical, chemical, and biological properties for example specific textural, and compositional properties (Boggs 2006) which are responsible for the formation of sedimentary facies. However, some specific or uncertain depositional environment requires the combined assessment of many different characters of the formation and cannot only be dependent on facies analysis.The Cretaceous Moro Formation along with the Cretaceous Pab Formation is an important reservoir. Both Formations are active reservoirs in the Pir Koh, Sui, and Loti gas fields of the Lower Indus Basin of Pakistan. The Moro Formation is also acting as a secondary reservoir in the Lower Indus Basin. Some researchers for example (Sultan and Gipson 1995; Eschard et al.2004) have worked on the Moro Formationin terms of its sequence stratigraphy and petroleum aspects. This paper is an approach to explore the Moro Formation in terms of its Sedimentology and composition. Additionally, the petrographic analyses along with lithofacies analysis were carried out for the determination of provenance.This article also assesses the petrographic analysis and procedures to recognize the depositional environment, provenance analysis, and vertical lithological profiling of the Moro Formation which were measured in the Eastern Sulaiman Range (Fig 1). Litho-facies investigation of the succession was done for the Moro Formation employing a revised form of Miall facies schemes (Miall 1985, 1996).

2. Geological setting

The Sulaiman Range is situated along the compressional zone in the north-western part of the Indian plate. This compressional zone is developed because of the oblique collisional movement between the two, the Indian plate and the Afghan block (Allemann 1979).The degree by which this oblique movement was done was an anti-clockwise rotation of 120˚. Because of this oblique movement, the lobe-shaped Sulaiman and Kirthar Ranges are formed (Yeats et al. 1984). The Cretaceous

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and Eocene sequence developed during the early collision of the Indian plate and the Afghan block. Between the rocks of the Cenozoic and Mesozoic age of Upper-Indus-Basin and Lower-Indus-Basin, an unconformity was also developed which is known as K.T-Boundary (Hunting Survey Corporation 1961; Yeats and Hussain 1987). The Sulaiman Range included two main structural elements which are Sulaiman Fore-deep and Sulaiman Fold-belt (Kazmi and Rana 1982; Abdel1971) (Fig 2 and 3). The syncline landscape in which the Eastern limb is gently developing a monoclinal structure and the sharper western limb is named as Sulaiman Fore-deep. Along the East direction of the Indus River, the Monoclinal structure of the Sulaiman Fore-deep extends on 25.0 kilometers (Humayon et al. 1991). The Sulaiman Foldbelt structure is different from the Sulaiman Trough or Lobe and these two are separated by the Kingri-Fault (Hunting Survey Corporation 1961). The Sulaiman Foldbelt structure and the Sulaiman Trough are developed from East to West and are perpendicular to tectonic actions (Jadoon et al. 1989). In the core of the Sulaiman Fold-belt (Fig 2), blind thrust is present, like the one that is mapped in the Upper-Indus-Basin (Thompson 1981; Pennock et al. 1989). The main lithologies which are developed in the Sulaiman Fold-belt are (1) Neogene to Quaternary deposits (2) Phanerozoic to Eocene Deposits (Kazmi and Rana 1982)(3) Upper-Eocene-lower-Eocene series.

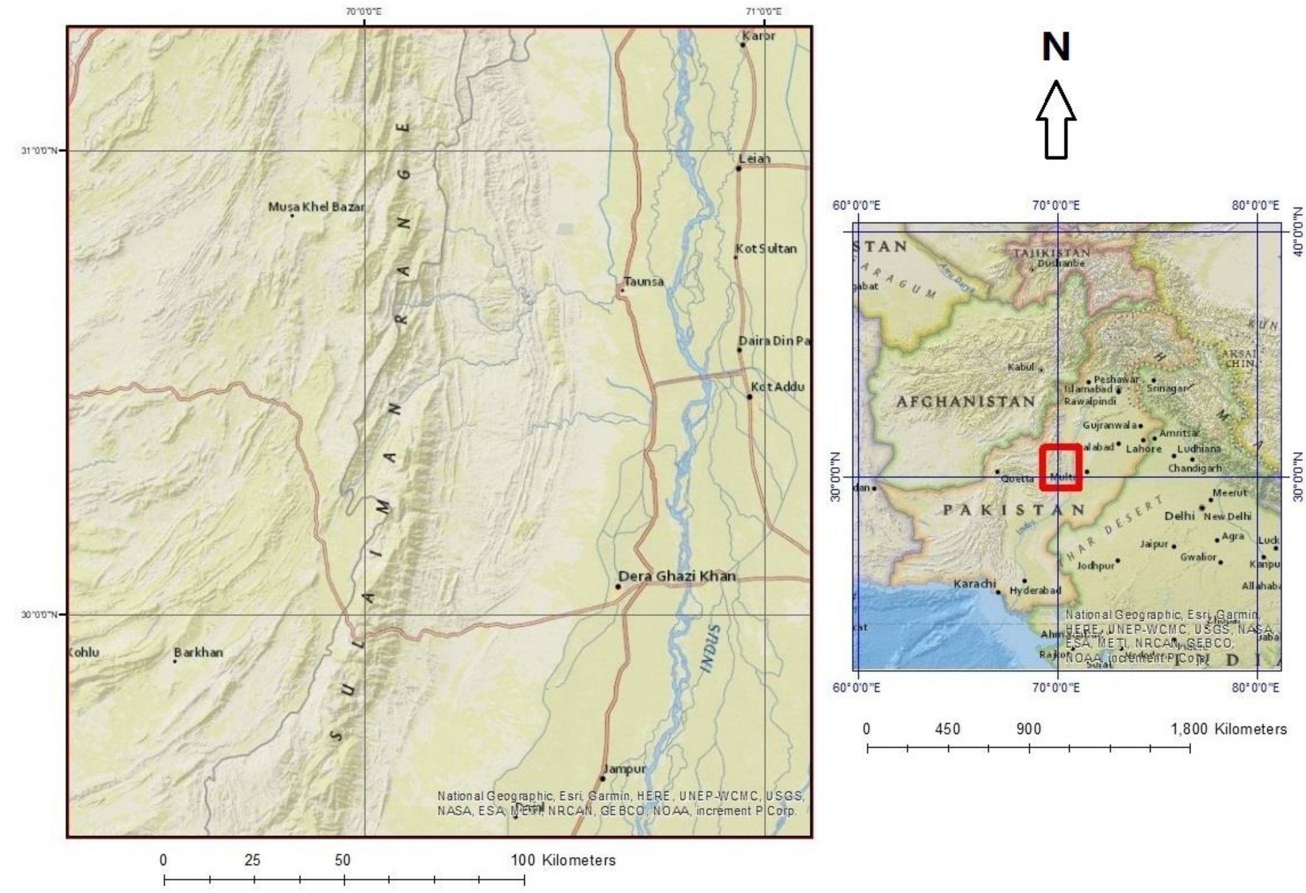

Fig 1. Outcrop belt of the Moro Formation in the Eastern Sulaiman Range of Pakistan showing the location of the measured section.

3. Material and Methods

Extensive field work was carried out to identify the different facies in the formation. A total of 12 lithofacies were identified in the formation based on the lithological variation. During the field work thoroughly mapping of the formation have been carried out and a detailed lithological log was created to summarize the formation characteristics. Field samples were collected from the Rakhi Gorge section for the purpose of comprehensive petrographic studies . A total of 37 samples were collected. The thin sections were prepared from these samples and were studied under a microscope by point counting method with a division into 400 point counts per section. Microsoft Excel was used for the statistical analysis of the data. QmFLt and QFL diagrams were used to identify the composition, classification as well as the suggested provenance areas for the studied samples from the formation.

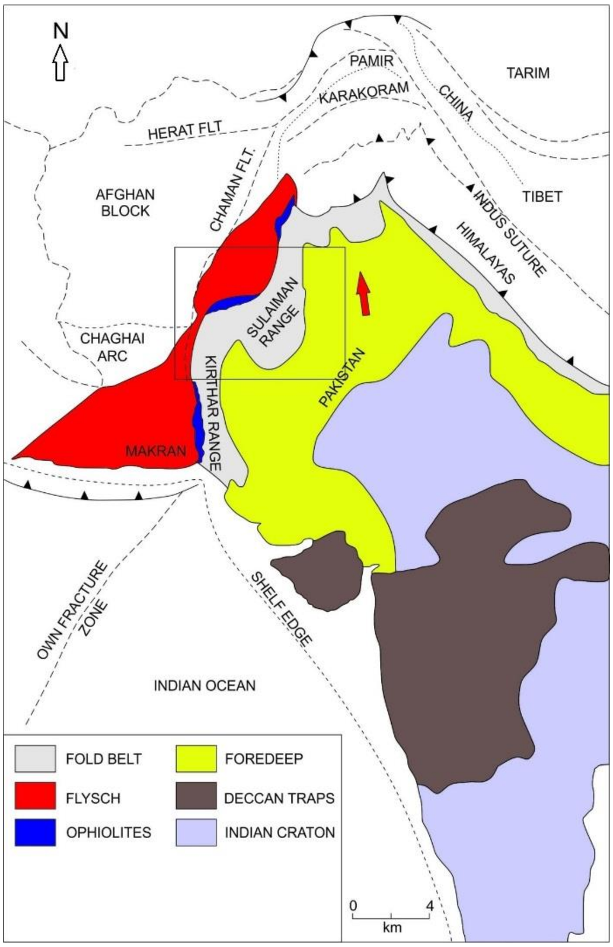

Fig 2. Tectonic setting of Pakistan and the Sulaiman fold belt (modified from Stonely 1974; Powell1979; Kazmi and Rana 1982), showing the position and lobate shape of the Sulaiman Range on the western edge of the Indian subcontinent.

4. Lithostratigraphy

The name Moro Formation (Lower Ranikot Formation), The "Limestone with Hemipneustes sp." of Vredenburg (1909) was introduced by Hunting Survey Corporation (1961), after the Moro River that flows between Johan and Bibi Nani. Fatmi (1977), records the details of the Moro Formation in which he stated that the Moro Formation contains grey, thin-medium to thick-bedded, sandstones, grey-dark grey mud, dark grey to grey shale. Sandstones, conglomerates, claystone, and shale are the main lithologies of the Moro Formation. The main lithology in the Sulaiman Range is sandstone containing also iron-rich? interbeds. The Moro Formation conformably overlies the Pab Sandstone with a gradational contact wherever the two units are in contact. However, where the Pab Sandstone has not developed the formation either conformably overlies the Fort Munro Formation (northeast of Pui) or disconformably the Parh Limestone (Moro River-Bolan Pass). The contact is marked by a conglomerate that is 10 to 90 cm thick and consists of small angular chips to rounded cobbles (up to 15 cm) of the underlying Parh Limestone embedded in greenish grey shale. The Moro Formation, in its type section, is overlain disconformably by the Khadro Formation (Hunting Survey Corporation 1961) and the contact is marked by a basal algal conglomerate of the latter unit (Hunting Survey Corporation 1961). The age of the Moro Formation ranges between Maastrichtian and Late Cretaceous.

5. Lithofacies

Sediments of the Moro Formation in the Eastern-Sulaiman-Range, characterized by a range of lithofacies that preserve a record of depositional environments. Twelve litho-facies are recognized in the Moro Formation, using the Miall-classification-scheme (Fig 3 and 4) (Miall, 1985 and 1996). The main characteristics feature defining all these lithofacies are the lithologies, sedimentary structures, sediment grain sizes, and thickness of beds (Fig 5 and Table 1 and 2).

Table 1. Showing lithofacies in Moro Formation.

Facies No.	**Facies Code**	**Facies Description**
Facies 1	Gm	Clast-supported massive conglomerate
Facies 2	Gms	Matrix-supported massive conglomerate
Facies 3	Sm	Massive sandstone
Facies 4	Sl	Laminated sandstone
Facies 5	St	Sandstone with trough cross-bedding
Facies 6	Sp	Sandstone with planar cross-bedding
Facies 7	Sr	Sandstone with ripple marks
Facies 8	Ml	Laminated mudstone/shale?
Facies 9	Msc	Carbonaceous mudstone/shale
Facies 10	Lf	Limestone, Fossiliferous
Facies 11	L2	Limestone, No fossils
Facies 12	P	Pedogenic-feature/paleosol

Conglomerates having clast derived from sedimentary, metamorphic, and igneous rock fragments. These clasts are rounded-subrounded to subangular and range in size from 0.5 to 2cm. Fine to coarse-grained, medium-thick up to massive sandstone beds are of light-dark grey, brownish and dark colors. This sandstone is arkosic to sub-arkosic, and grains are poorly to moderately sorted. Laminated shale beds of greenish-grey to dark grey ranging in size from ten centimeters up to two meters, in places are interlaminated with thin, red, brown, dark grey, and dark green siltstone layers are also present to form shales.

6. Facies Cyclicity

In the Moro Formation two types of cycles have been described previously, (i) small sedimentary cycles that developed from channel migration or through the deltaic process and these processes are commonly autogenic, and (ii) large sedimentary cycles were generated through allogenic processes (Atchley et al. 2004; Cleveland et al. 2007; Ghazi and Mountney 2009). Small-scale cycles in the Moro Formation exhibited a fining-upwards trend. Such cycles are characterized through field studies and field mapping and the twelve litho-facies were mapped and recognized in the formation which are massive conglomerate, clast-supported, sand matrix-supported, massive sandstone, laminated sandstone, trough cross-bedded sandstone, planar cross-bedded sandstone, rippled fine-sandstone, laminated mudstone, fossiliferous limestone, unfossiliferous limestone and paleosol (Fig 3 and 4).

Table 2. Showing detailed lithofacies description and interpretation in the Moro Formation.

Facies	Faciesdescription	Interpretation
Facies 1: Gm Figure 3A	These Facies consist of massive Conglomerate, sandstone, and interbedded shale, conglomerate size 2cm, and top of the sandstone ripple marks are present, the bed surfaces are highly Bioturbated. The color on the weathered surface is greyish, brown and the color on the fresh surface is deep-greyish, Reddish. Different types of feature which is observed are Bioturbated at places and slightly fractured. The beds are thin to thick-bedded up to massive, contains Conglomerates which is clast supported, clast is up to 2 cm. At base, the subordinate boundary of litho-facies is with Litho-facies Fl and F1 that present above the Pab Formation (unconformity), the upper boundary is sharp and is with F1 and Sp. At base Gm Mark the contact between Pab and Lower Ranikot Formation. The geometrical shape of the lithofacies is wedge or Lenticular-shape.	This facies is deposited through high density/energy flow like channel deposits and shows that it is developed through uni-directional flow (Oguadinma, V. 2014).
Facies 2: Gms Figure 3B	These Facies consist of Massive Conglomerates Red soft recessive sandy ferruginous mudstone/ Siltstone, sand grains are poorly sorted sub angular fine-medium occasional coarse quartz, and Massive, fine-grained, sandstone bed in the matrix. Weathered Surface- reddish, yellowish, Fresh Surface- greenish, brownish. Different types of feature or sedimentary structure are observed which are Gravity structure and in sandstone ripple marks are present. The different types of internal features are recognized like Gravel, massive, sand matrix-supported, course-grained, and hard. The subordinate boundary of this litho-facies is with Litho-facie Sm and is sharp and flat, the upper boundary is sharp and is with facies Sr and Fl. The geometrical shape of the lithofacies is tabular or Lenticular-shape.	This facies is deposited through high-energy flow like channel deposits and shows that it is developed through uni-directional flow. The coarsening-upward cycles suggest that it was deposited in a deltaic setting (Allen 1963).
Facies 3: Sm Figure 3C	These Facies consist of compact, massive bedded sandstone, which is bioturbated on top. Calcareous sandstone, abundant fossil shells. The color on the weathered surface is dark-reddish brown, and Fresh-surface-color is Reddish, Dark black, and greyish. Different types of feature or sedimentary structures are observed which Gravity structure and Bioturbated. The different types of internal features which are recognized that the sandstone is Hard, compacted, massive bedded, Fine to Medium grained, which are bioturbated on top. Some fossils are also recorded in this facie. The lowermost contacts of the Lithofacies at different interval is with lithofacies Gm and FL and Upper boundary is with facies Gms, Sp and FL. The geometric shape of these facies occurs as a thick-wedge shape.	Massive sandstone is believed to be deposited in deep-marine setting in which the following mechanisms are involved (Stow and Mayall 2000; Stow and Johansson 2000): (1) deposition from Debris-flow i.e. rapid deposition (2) Deposition from turbidites i.e. Turbidity current deposits (3) deposition from traction current. In these, all turbidity currents are the most favorable mechanism for the deposition of massive sandstone (Allen, 1964; Walker and James 1992).
Facies 4: SL Figure 3D	These Facies characterized by Medium dark grey weathering yellowish-grey moderately hard, ledge-forming poorly structured well-sorted very fine weakly calcareous quartz arenite with brown clay matrix containing planktonic forams and light bluish-grey weathering light green relatively soft, recessive shale, siltstone, and mudstone with clay nodules arranged in meter-scale coarsening, thickening and cleaning upward cycles. At middle alternate beds of black Shale and Sandstone, thinning upward, few clay nodules, sandstone is very minute calcareous, Iron rusting in black shale. , Weathered Surface-grey, blackish, and Fresh Surface- blackish, grey, dark grey. Different types of feature or sedimentary structure are observed that sand is Laminated, Verticle fractures, and bioturbated, some shale is also present which contain nodules. The different types of internal features are that the beds are massive at the top, Fine to Medium grained, hard, and cliff-forming. The Lower-contact of these lithofacies is erosive with lithofacies Fl and the Upper is sharp with lithofacies Fsc.	This facies is deposited from suspension. When there is no traction current the water has sediment and made suspension then laminated sandstone is deposited. If plant debris is present then it shows that terrestrial or transition environment. And if ichnofossils are recorded then its shows that it is deposited from Fresh-water or deposited from Brackish-water. (Potsma 1986; Buatois et al. 1999).
Facies 5: St Figure 3E	This lithofacies is present only in the lower portion of the Moro Formation (Lower Ranikot Formation). This facies is medium-grained sandstone and at some places coarse-grained and interbedded with mudstone levels? and bioturbated, and is blackish, light grey to dark grey. They have thick trough sets. Internally they are fine-medium grains and thick-bedded. The lower boundary is with lithofacies Gm, Sr, FL, and the Upper boundary is with lithofacies Sp and Fl. Geometry wedge shape?	The deposition of these lithofacies occurs from storm currents. These lithofacies show a high-energy environment. The coarsening-upward cycles and the beds are thick as we go upside this shoe that it was deposited in a deltaic setting (Ghazi and Mountney 2011).

Table 2. Continued

Facies 6: Sp Figure 3F	Light brown thin-thick bedded, hard, ledge forming well-sorted medium Quartz Arenites with intensely burrowed bases medium-grained moderate-well-sorted sandstone beds, and at center alternate thin-bedded sandstone siltstone, mudstone, and shale (Bioturbated). Hard, Coarse or pebbly at the base, Thickening upward. Mud clast and fossil shells. , Weathered Surface- yellowish, reddish, grey, greenish Fresh Surface-Reddish brown, olive-grey, dark grey. Feature/Sedimentary Structures that are recorded are thick planner cross-bedded sets, with small ripple marks, bioturbated beds, and have verticle fractures. Internal features grains are poorly sorted sub angular fine-medium occasional coarse, wavy bedding. The lower contact of this facie is sharp with lithofacies S-t, Gm, Sr, S-m, F2, Fsc, and FL and the upper contact is with lithofacies Fl, FL, (Marked contact between Lower and middle Ranikot) also with Sr, F2, and Gm. The geometric shape of these lithofacies is Lenticular-tabular.	Amalgamated planner crossbedding suggest deposition from flows related to high energy condition. The planar cross-beds show distributary-mouth-bar deposition. Lower-flow-regime is the part where planner cross-beds are deposited. This shape and depositional setting of planner cross-beds suggest that it was also deposited in a channel setting.
Facies 7: Sr Figure 4A	These Facies are characterized by alternate beds of Sandstone passing up into quartz wacke and Shale with Breccia, thinning upward, Top Ripple marks, Clay Nodules (40cm-1m), and Chert Nodules, Gravity/Deformation/Flow structure, Bioturbated. Shale, Olive green, grey, Sandstone, the color of weathered Surface is brownish, greyish, reddish, and color of the fresh surface is grey, greyish, brown. The different types of feature/Sedimentary Structures are dominantly ripple marks, ripple cross-laminated at the base have planner cross-beds, bioturbated. And internally they have thick-bedded, thinning upward bed, hard, and cliff-forming. The lower contact of this facie is sharp with lithofacies Sp, FL, Gms, and F1 and the Upper boundary is sharp with facie Sp, St, Fl. Geometrically this facie is Thin, discontinuous, and wedge shape.	This facies is caused by out-of-phase deposits with bedform during lower flow regime. The Sr includes exclusive features of small-scale ripples this shows that the current is from two directions (i.e. Ebb and Flood current) (Potsma, 1986; Buatois et al., 1999). The Sr lithofacies show deposition in a tidal environment, also deposits in a channel setting and beach environment.
Facies 8: Fl Figure 4B	These facies are characterized by alternate beds of shale, mudstone, and siltstone. Light bluish grey soft recessive bulky calcareous mudstone and shale containing clay nodules with alternate medium-dark grey, weathering yellowish-grey thin platy very fine limestone occasional with benthic forams Greenish, grey, black on the weathered surface, olive green, light green, grey, and black on a fresh surface. Feature/Sedimentary Structures are mud cracks, Clay and Iron Nodules. Internal features are variable stacking patterns of small-scale sediment packages. The lower contact of this facie is with lithofacies St, Sp, Sr, Sm, F1, F2, and Gm and the upper boundary is with lithofacies Sl, Sp, Sr, Sm, F1, F2, and Gm and the boundary is sharp. Geometrically this facie is thin, sheet-like packages.	This facies is present in restricted estuarine basins or restricted offshore transition. This facies is deposited from suspension (Potsma 1986; Buatois et al. 1999).
Facies 9: FscFines, carbonaceous Figure 4C	These Facies consist of Shale and alternate sandstone beds, upper bed contact is sharp and lower is also sharp, have Iron stains. Weathered Surface- blackish, greyish, Fresh Surface-light blackish, dark brown. The different types of feature/Sedimentary Structures are carbonaceous and clay nodules. Internal features uniform verticle grain size. The lower contact of these lithofacies is sharp with facies SL and the upper boundary of this lithofacies is with lithofacies Sp and is sharp. Geometry is Sheet.	Fine carbonaceous is show restricted estuarine basin or restricted offshore transition. (Potsma 1986).
Facies 10: F1 Limestone, Fossiliferous Figure 4D	This Facies consists of Light bluish grey soft recessive bulky calcareous mudstone and shale containing clay nodules with alternate medium-dark grey, weathering yellowish-grey thin platy very fine limestone occasional with benthic forams. Feature recorded as they have little laminated. Internal features thick-bedded limestone/Sandy limestone. The lower-contact of these lithofacies is with lithofacies Fl, Sp, Gm, and the Upper boundary is with facies Sr, Fl, P and is sharp. Geometrically this facie is Lenticular, Rarely wedge shape.	The fossiliferous limestone deposited Inter-tidal shoal or channel over bank shallow sub-tidal shoal storm deposits (Tucker 2003). The limestone which has fossils are deposited on a platform which has carbonate-rich which are influenced by wave and tides. The main calcareous material is skeletal materials (Poursoltani and Oskoian-Shirvan 2015; Schlager 2004).
Facies 11: F2 Limestone, No fossils Figure 4E	These Facies consist of Grey hard ledge forming erosive-based limestone and Brown graded limestone bed with Mudstone which contains clay nodules and siltstone have Iron nodules. , the color on the weathered surface is greyish, greenish, and on fresh-surface grey, green, brownish. No Feature/Sedimentary Structures are present in this facie. Internally this facie is thick-bedded limestone/Sandy limestone. The lower-contact of these lithofacies is with facies Fl, Sp, and the upper boundary is with facies Sp, Fl, and sharp. Geometrically this facie is rarely wedge shape.	The main mechanism through which carbonates are deposited is where the rate of calcareous input is very high and there is less deposition of Siliciclastic and other detritus (Adeigbe and Salufu 2009).
Facies 12: P Pedogenic feature or paleosol Figure 4F	This Facies consists of very thin-bedded Siltstone paleosols interbedded with very silty fine-grained to very poorly sorted quartzite. Seven different layers have been observed showing color variation, and the Bottom 7m is very marly with lignite fragments. The different types of feature/Sedimentary Structures are Rootlets, Columnar, blocky. Internally this facie is Very silty fine-grained to very poorly sorted. The lower contact of these lithofacies is with facies Sp and the upper boundary is with lithofacies F1, Fl, Gm. Geometrically this facie is Thin to the thick sheet-like packages.	Paleosols are very important for the interpretation of the environmental condition, it is used to interpret the stratigraphic sequence of how chemical, biological, and clastic sediment are arranged. If iron concretion, Rhizoliths, and nodules are present in Paleosole then it shows that it is genetically existing in sedimentary strata but not all the time. For the interpretation of paleosols, the characteristics features are soil horizon, root traces, and soil structure. These all features are count when study paleosol. (Retallack 1988; 2001, Gustavson 1991).

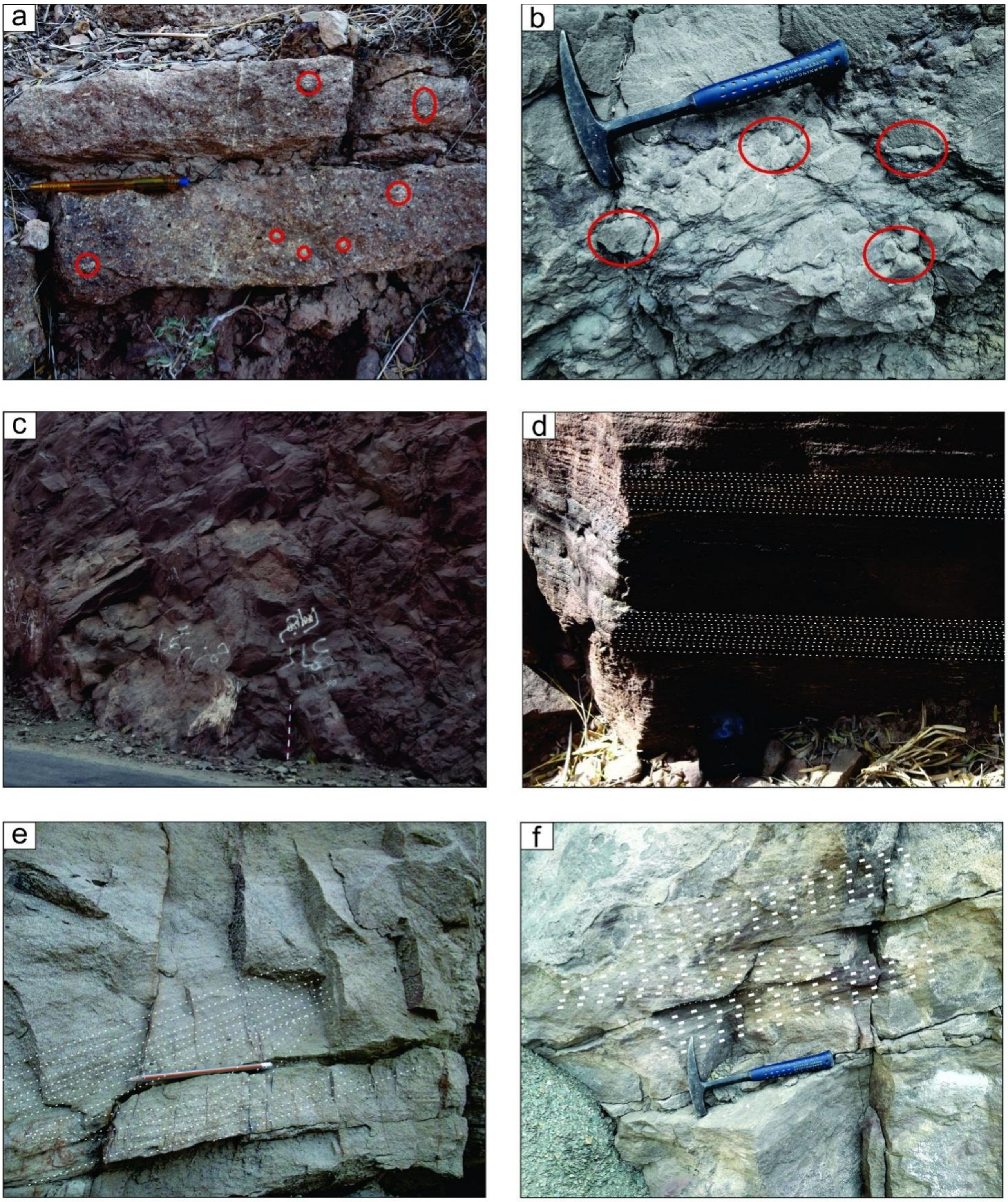

Fig 3. Facie field pictures showing as, a) Gm, b) Gms, c) Sm, d) Sl, e) St, f) Sp, lithofacies types encountered in the MoroFormation, Eastern Sulaiman Range, Pakistan.

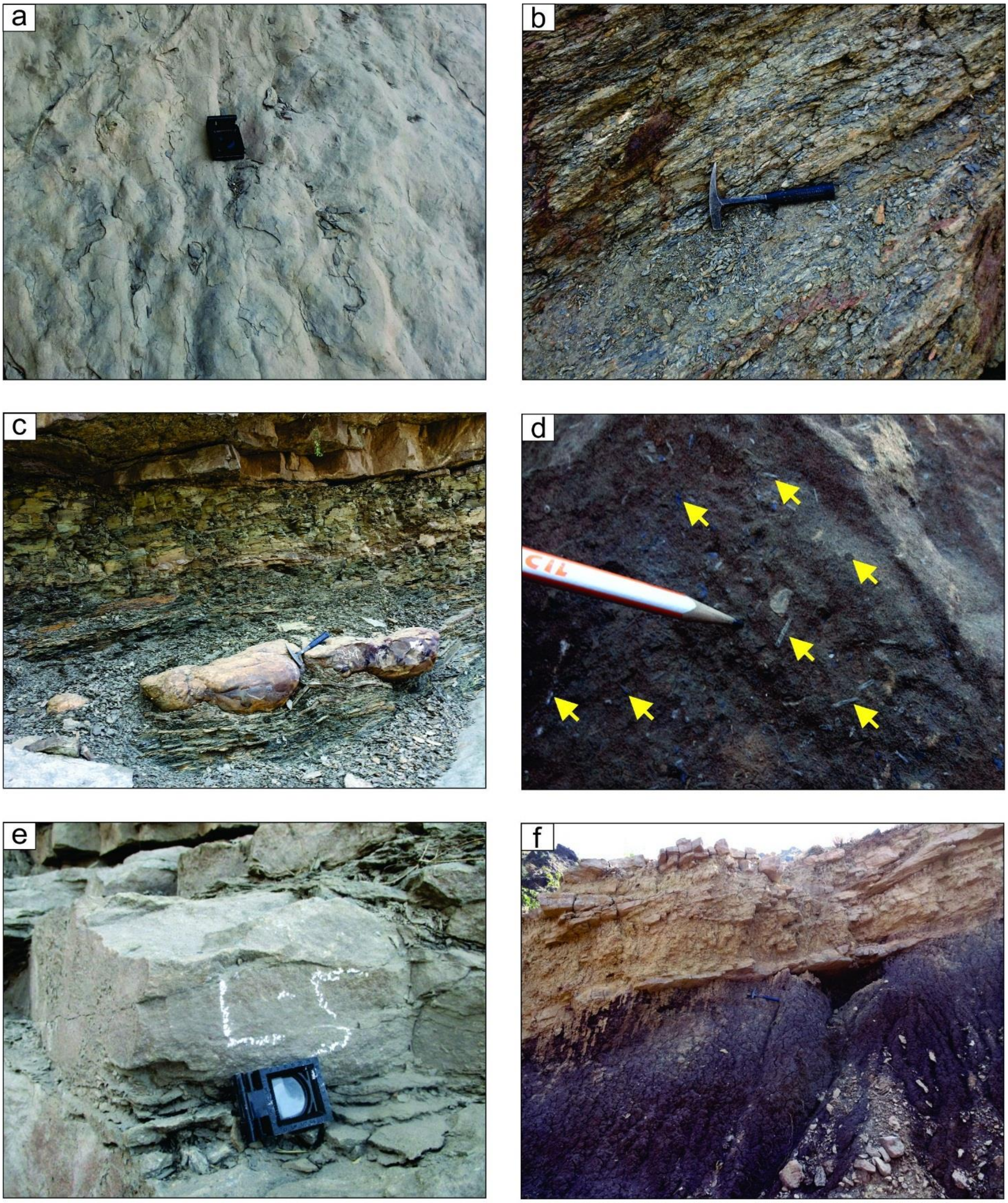

Fig 4. Facie field pictures showing as, a) Sr, b) Fl, c) Fsc, d) F1, e) F2, f) P, lithofacies types encountered in the Moro Formation, Eastern Sulaiman Range, Pakistan.

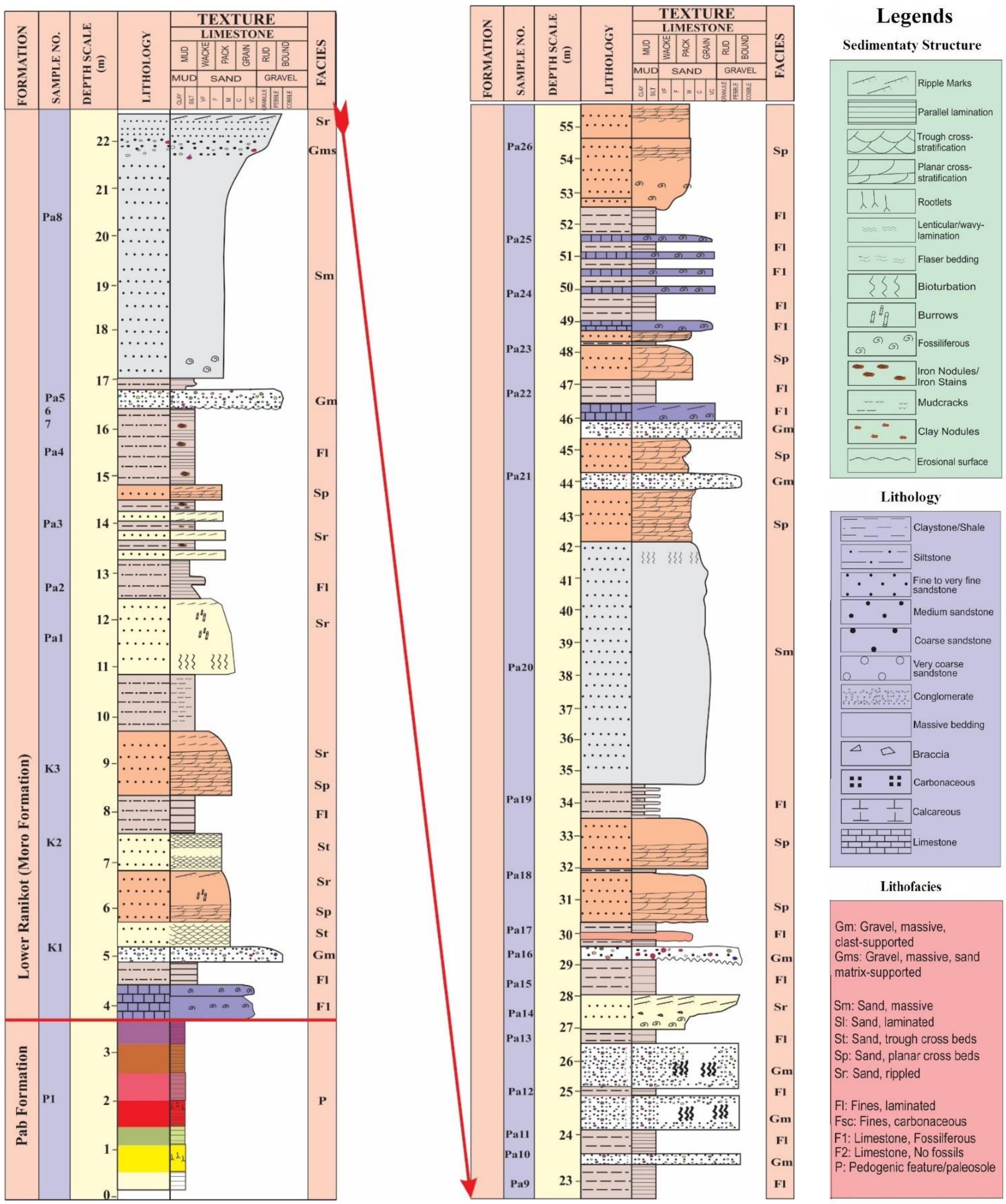

Fig 5. Sedimentological log showing facies changes in the Moro Formation, Eastern Sulaiman Range, Pakistan.

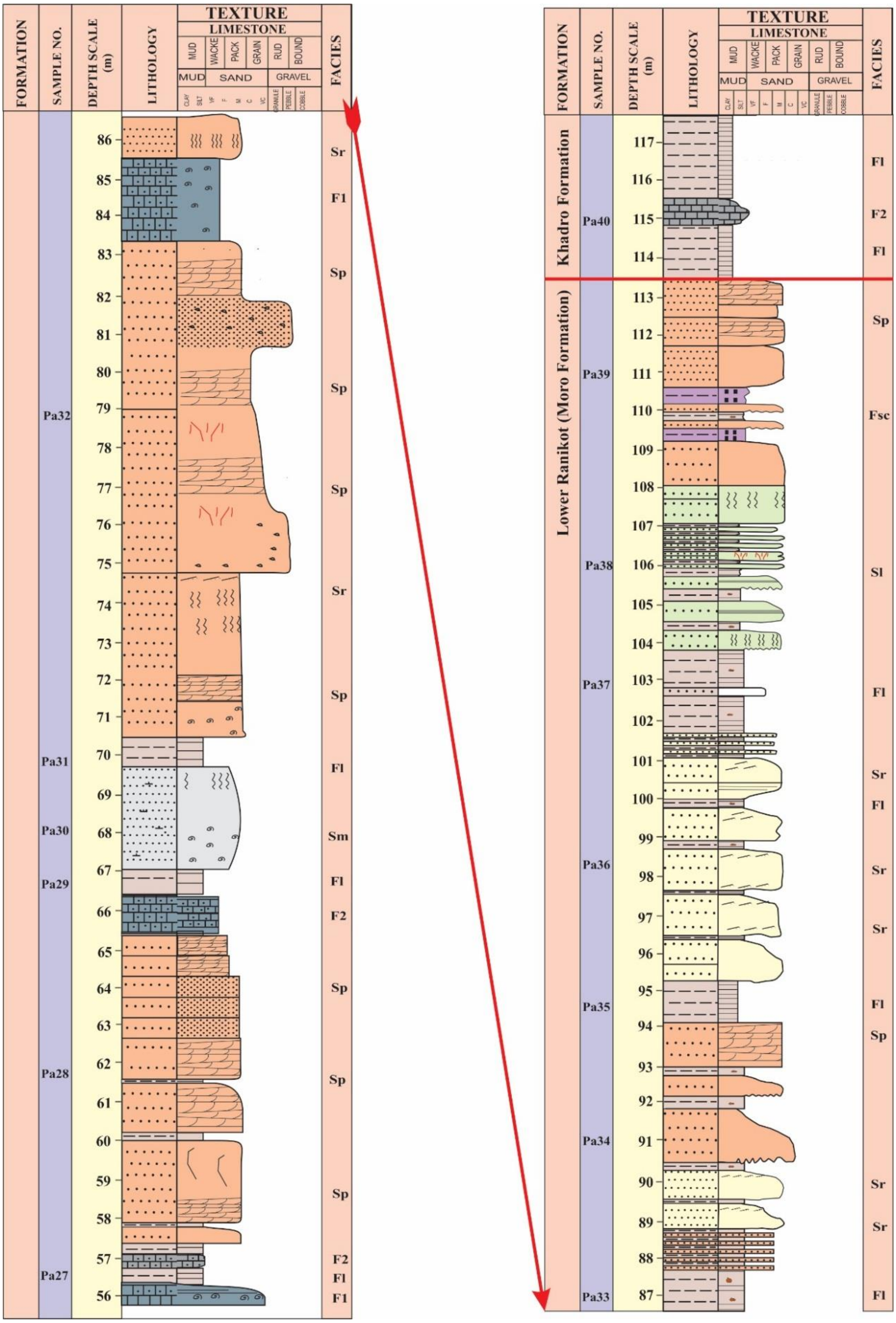

Fig 5. Continued.

7. Petrographic analysis

The most abundant lithology of the Moro Formation is sandstone which is about 66% of the unit volume. Textural properties recorded within the Moro Formation generally exhibit medium to packed and grain size ranging from fine to very coarse-grained. The contact between grains is concave to convex, sutured, and tangent contact is observed. For petrographic observation of sandstone, the main detrital constituents are quartz having two types' monocrystalline and polycrystalline, feldspar of the negligible amount, and other crystal clasts like magnetite, hematite, and shelly-skeletal fragments that have been recalculated into 100% based on sandstone classification in QFL (Quartz, Feldspar, Lithic) and QmFLt (Quartz Monocrystalline, Feldspar, Lithic) diagrams of Pettijohn et al.(1987) (Fig6). This analysis shows that quartz is the most abundant in all studied thin sections. Detrital mineral composition shows that in Moro Formation, sandstone is litharenite (McBride 1963). The average modal composition of the sandstone of the QFL diagram was Q 66% F 0.3% L 33.7% and that of the QmFLt diagram was Q_M 57% F 0.23% L 43.77%. The overall average composition is Q 61.5% F 0.27% L 38.7%. A total of 37 thin sections are studied for Petrographic analysis, out of which two samples are fall in the sublitharenites category, twenty-seven samples are considered as litharenite, and eight quartz arenite categories are identified.

8. Provenance

To introduce the provenance of the sandstone, the recorded proportion of detrital grains are plotted on QFL (Quartz, Feldspar, Lithic) and QmFLt (monocrystalline quartz, feldspar, lithic) diagrams like Dickinson and Suczek (1979), (Fig 6). For Provenance analysis Dickinson et al. (1983), schemes are used and for the interpretation of the tectonic situation. Ingersoll et al (1993) elucidations are adopted. Based on QFL and QmFLt diagrams of Dickinson and Suczek (1979), the source area for Moro Formation was quartz recycled to the cratonic interior (Fig7) (Dickinson 1985). However, the provenance shows that the 27 number of samples fall in litharenite category, this shows recycled, or craton interior origin (Lithic-recycled or Transition) source area (Fig7), sublitharenites category identify in two samples suggesting quartz recycled source area and eight quartz arenite categories are identified which is indicative of a craton interior source area (Fig6) (Dickinson and Suczek 1979).

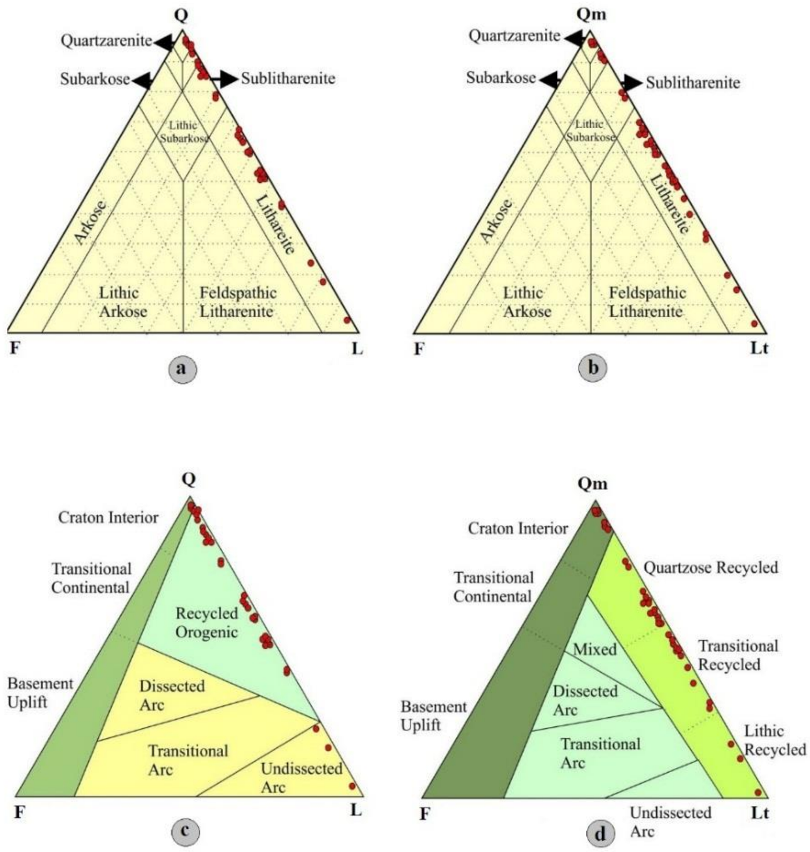

Fig 6. QmFLt and QFL diagrams showing the composition, classification as well as the suggested provenance areas for the studied thin sections. a-b) are modified from Pettijohn et al.(1987) while c-d) are modified from Dickinson and Suczek(1979).

For identification of the source area of the Moro Formation petrographical studies were carried out. The composition of sandstone and clasts showed that the source area does not change over time, based on these analyses the quartz grains in the Moro Formation originated through recycling and erosion of igneous and metamorphic rocks (Dutta 2007). Undulatory extinction is observed in grains which is evident of plastic deformation, shows a significantly tectonic-uplift of crystalline-basement rocks within the source area (Fig7). Medium-coarse grain, mono-crystalline quartz (Fig 9 a and b) are originated from granites (Dickinson 1985; Dutta2007; Basu et al. 1975), While mono-crystalline quartz of fine-grained was derived from pieces and fragments of large quartz grains of igneous and metamorphic origin. And elongated, stretched poly-crystalline quartz-grains having metamorphic origin (Poursoltani and Fursich 2020; Ghazi 2009) (Fig 7). The large-scale sedimentary cycles represent phases of regression and transgression of sea-level recorded during the stratigraphic interval (Fig 5). The Cretaceous and Eocene sequences developed during the early collision of the Indian plate with the Afghan block. Between the rocks of the Cenozoic and Mesozoic age of Upper-Indus-Basin and Lower-Indus-Basin, an unconformity was also developed and called as K.T-Boundary (Yeats and Hussain 1987; Hunting Survey Corporation 1961; Powell 1979). The arrangement of facies into fining-upwards-cycles characterized via a discrete set of lithofacies, all supported the assumptions that the Moro Formation was deposited in a deltaic to the shallow marine environment (Ghazi 2009). The sedimentary origin quartz has rounded to well-rounded grains (Basu et al. 1975). Feldspar fragments were indicative of igneous and metamorphic source area, most likely acidic igneous, granite or gneiss (Ghosh and Kumar 2000; Basu et al. 1975). Plutonic rocks of granitic configuration and metamorphic rocks of low grade most likely gneiss, schist, and quartzite are the sources for micas (Ghazi 2009; Ghazi and Mountney 2011).

9. Source rocks

The mineralogical data and Qm, F, Lt diagram of Dickinson and Suczek (1979), (Fig 6 and Fig 7) shows that most of the grains in the Moro Formation were derived from igneous and metamorphic zones. The sedimentary origin of the quartz having rounded to well-rounded grains (Basu et al. 1975) that were possibly derived from reworking of Cambrian or Pre-Cambrian sedimentary rocks. Hot climate, erosion, and moderate relief were all recorded in this study, which shows that the Malani range was the best fit for the source area of the Moro Formation.

10. Depositional setting

The Moro Formation was settled on the western northwest-facing of the Indian Plate. The Cretaceous and Eocene sequence developed during the early collision of the Indian plate with the Afghan block. Deposits of tertiary age were formed during the collision of Indian plate with the Laurasian plate, transgression and regressions were also observed during that time. Based on lithofacies the depositional environment was interpreted as near-shore shallow water, marine environment (Ahmed 1997). The succession is 110-140 meters thick and is primarily composed of fine-coarse grained sandstone, minor-siltstone, mudstone (claystone, shale), and limestone. Different lithofacies are identified and based on lithofacies and petrographic investigation it is interpreted that the depositional environment for Moro Formation ranges from Deltaic to Marine setting (Delta Plain-Delta front) (Fig 8). The most common feature in the Moro Formation on the basis of which the correct depositional environment was interpreted is sedimentary structures. The formation excellently consisting planner cross-bedding, laminations, sandstone having bioturbation are recorded in the Moro Formation, with plenty of coarse to very coarse, some pebbly sandstone having massive beds, are all the indicative of storm reworking sediments, high-density, unidirectional flows, and suspensions settling (Oguadinma, 2014).; Ghazi and Mountney 2009) (Fig 8). In the deposition of the Moro Formation, the storm process has played an important role., i.e. planner cross-bedding, lamination parallel laminated sandstone beds and sandstone having bioturbation are derived from storm reworking and suspension sedimentation and through traction transportation (Reineck and Singh 1972; Nelson et al. 1982). Massive and thick sandstone have resulted completely through storm reworking (Mulder and Alexander 2001; Kassem and Imran 2001). Channels deposits in the Moro Formation consist of extremely erosive, amalgamated, and aggradational indicating a high energy flow condition, which shows the bypass process.

The sedimentary facies within the Moro Formation characterizes the sequential event of different depositional environments within the deltaic structure (Delta Plain-Delta front) at a given point (Fig 8). The grouped cross-stratified sandstones are substratum sediments deposited in the channelized zones (facies Gt, St, and Sp). Ripple cross-laminated sandstones represent predominantly levee-type sediments (facies Sr). Fine-grained horizontally cross-bedded sandstone show deposition from over-sheet floods. Claystone with siltstone and fine-grained sandstone lenses represent floodplain sediments (facies Sl, Fl, and Fsc). The shale units, like coaly and glauconitic shale, represent swampy delta plain deposition. The presence of bioclasts and limestone in the Moro Formation show rise in the sea level with flooding of the delta with marine water deposits in the upper part. The arrangement of facies into fines-upward-cycles characterized by a diverse set of lithofacies, all the assumptions are shows that the Moro Formation deposited in a Deltaic (fluvial) to the shallow marine environment (Delta Plain-Delta front) (Ghazi 2009).

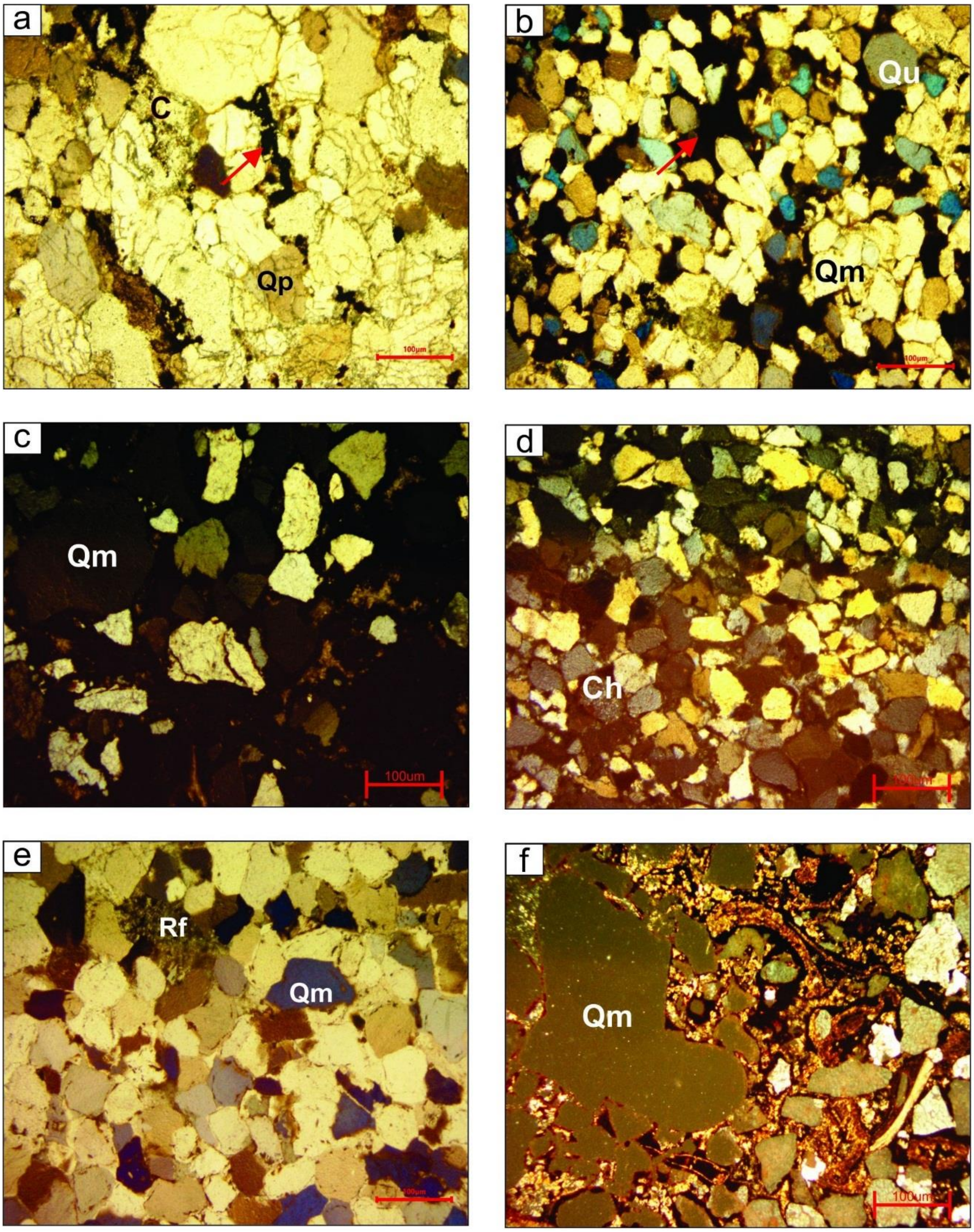

Fig 7. Thin-section photos of samples from Moro Formation in cross-polarized light (CPL) showing moderately well sorted, sublitharenites, and Quartz Arenite. The grains are usually subangular to sub-ground with a dominance of high sphericity, a) Showing Qp=Polycrystalline Quartz, Clay with organic content? and Hematite with arrows, b) Qm= Monocrystalline Quartz, Qu= Undulose extinction of quartz, c) showing quartz and different grain contacts, d) Chert, e & f) Showing medium and coarse-grained quartz and rock fragments.

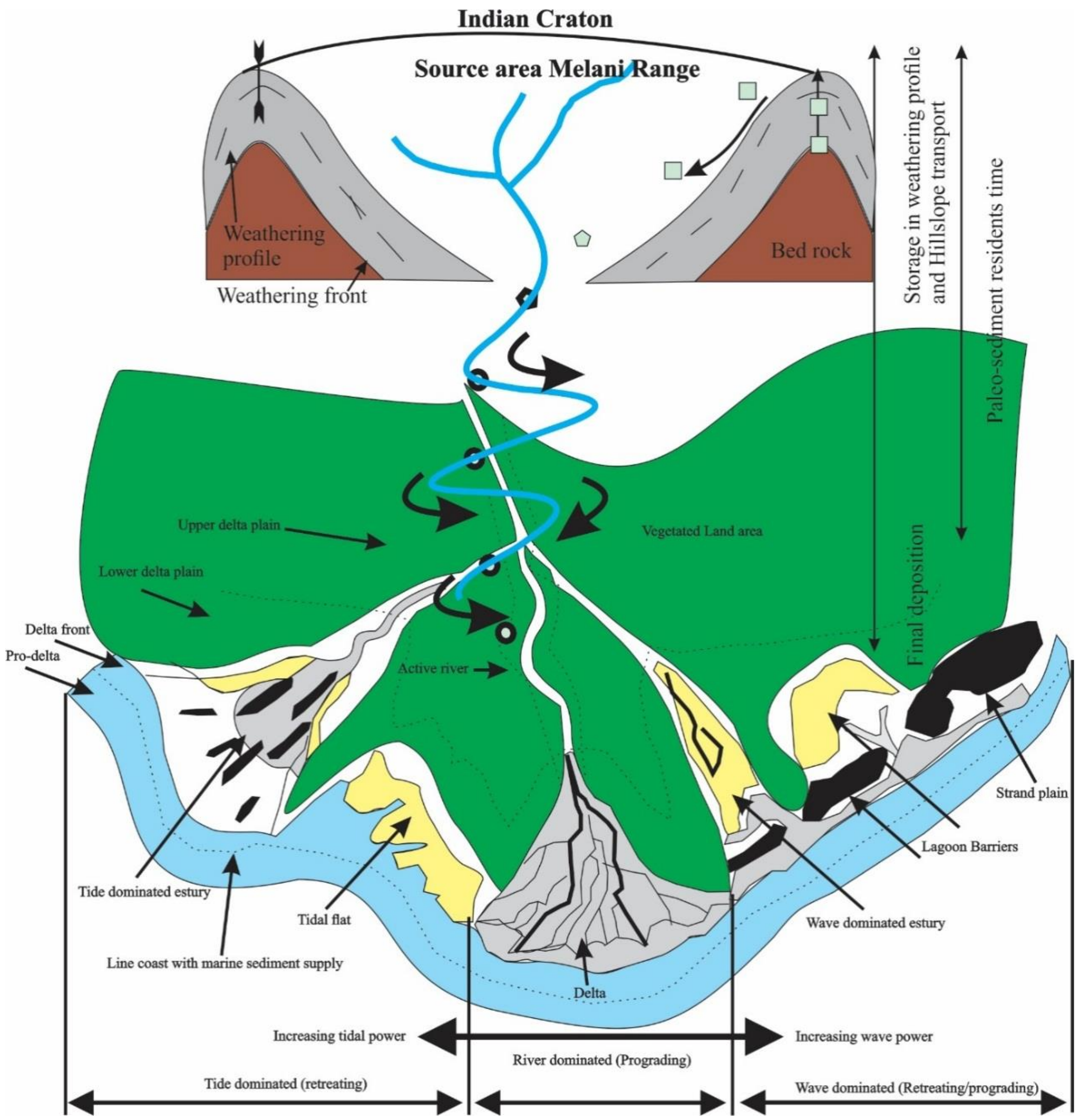

Fig 8. Generalized depositional model for the Moro Formation.

11. Conclusions

1. The sedimentary facies within the Moro Formation characterizes the sequential event of different depositional environments within the deltaic structure (Delta Plain-Delta front).

2. The field study and through the lithologic log, twelve litho-facies are characterized, which are Gravel, massive, clast-supported, Gravel, massive, sand matrix-supported, Sand massive, Sand Laminated, Sand trough Cross beds, Sand planner cross-beds, Sand rippled, Fines, laminated, Fines, carbonaceous, Limestone Fossiliferous, Limestone with No fossils and paleosol.

3. Detrital mineral composition shows that Moro Formation, Sandstone is Quartz arenite. The average modal composition of the sandstone of QFL Diagram was Q 66% F 0.3% L 33.7% and thatofQmFLt Diagram was Qm 57% F 0.23% L 43.77%. The overall average composition is Q 61.5% F 0.27% L 38.7%.

4. Based on QFL and QmFLt diagrams of Dickinson and Suczek, the source area for Moro Formation was Quartz recycled to the cratonic interior are recommended as source area.

5. The mineralogical data and Qm, F, Lt diagram, show that most of the grains in the Moro Formation were derived from igneous and metamorphic zones. The sedimentary origin quartz have rounded to well-rounded grains that were possibly derived from reworking of Cambrian or Pre-Cambrian sedimentary rocks. Hot climate, erosion, and moderate relief were all recorded in this study, which shows that the Malani Range was the best fit for the source area of the Moro Formation.

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